Integration simulation and control practice of a designed electric fertilization device for adapting different plant spacings

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Abstract: Effective adjustment of fertilization spacing and amounts for different plant distances is beneficial to increase production and reduce the amount of fertilizer used. In order to achieve such a target, an electric-fertilizing vehicle with staggered fan-shaped openings in a fertilization device is proposed here, and its fertilization spacing and amounts are controlled by a control system and mobile phone-based programs. Further validating multivariable effects on fertilization spacing and amounts, such as openings, rotary speeds, and moving parameters of the vehicle, an integration discrete element model (DEM) is established so that the feasibility of the fertilization device could be evaluated before manufacturing and testing. Finally, it is reflected through field-simulated experiments that fertilizer spacing ranges from 0.27 to 5.45 m. Compared with simulated results, the absolute error varies from −0.08 to 0.05 m, and the maximum relative error is about −5.67%. Therefore, the uniform and stable fertilization for different plant spacing is semi-actively achieved by the designed device and a control system with mobile phone-based programs. The proposed simulation model is feasible, thus presenting a good reference for designing these components.

Keywords: electric-fertilizing vehicle, staggered fan-shaped openings, mobile phone-based program, varied spacing fertilization, DEM

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1 Introduction

Low utilization rates of fertilizer, low production, environmental pollution, and other problems could be caused by unreasonable fertilization[1-3]. To avoid these problems, a large number of fertilization devices and their vehicles have been proposed. For example, trough wheel[4], spiral[5], rotating plate[6], and sprinkling[7] types of fertilization devices have been applied in fields of continuous-uniform fertilization. Most existing devices, including those mentioned above, are suitable for the same plant spacing and a high density of plants. Therefore, it is possible to apply them in maize and rice plants, and the root fertilization for them is always achieved[1,8]. However, these devices have poor adaptation for many plants, such as soybeans, tomatoes, peppers, cotton, figs, and so on, especially considering root fertilization for these plants. In order to obtain better versatility, other advanced technologies, including prescription maps, sensors, and their precision control methods, have gradually emerged[9]. In these schemes, the properties of plants and soils are determined, and the fertilization amount is regulated by measurement results of sensors in real-time, which is beneficial for accurate fertilization[9]. While these new methods have evidently improved fertilization accuracy, their cost is higher and their popularization is still very limited, especially for mountainous and hilly regions in countries with underdeveloped agricultural technologies.

Essentially, some fertilization devices with a good adaptability for different plant spacing and a low cost are also anticipated at this stage. However, the structure, performance, and control systems would be more complex, and a good method for evaluating feasibility of fertilization devices during the design stage is also crucial. In view of this point, discrete element models (DEM) and EDEM simulation programs are widely utilized in the field of agricultural machinery. Of these, single fertilizer particle motion simulations were achieved in EDEM[10], and parameters of crucial components in a fertilization device were optimized successfully[11]. Working parameters of a fertilizer drainer were also studied systematically[12]. It is concluded from existing EDEM simulations that there are few integrated simulations for fertilization amounts related to all parameters such as rotating speeds, openings, moving speeds, and steering angles.

In particular, simulation of the field fertilization scenario is usually not considered. All of these potential problems will result in a longer cycle of design and higher development cost.

Therefore, in this paper, an electric-fertilizing vehicle with a new fertilization device is developed for the requirements of different plant spacing and amounts, and the integrated control of vehicle speed, steering angle, and the opening and rotating speed of the disc can be achieved by a mobile phone-based program. Also, integrated simulations in EDEM are considered to estimate performance and optimize parameters. The details will be given in the following sections.

2 Structure and principle of an electric-fertilizing vehicle

As shown in Figure 1[13], an electric-fertilizing vehicle is mainly composed of electric drive subsystems (1), frame (2), fertilization

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subsystem (3), storage battery (4), electric steering subsystems (5), control subsystem (6), suspension subsystems (7), damper (8), spring (9), longitudinal stabilizer bar (10), and lateral stabilizer bar (11). The fertilization subsystem (3) contains 14 components, including seeding box (12), fixed frame (13), regulating mechanism (14), receiving tray (15), transmission shaft (16), shunt pipe (17), spiral hose (18), fertilizing motor (19), ditcher (20), fixed disc (21), adjusting disc (22), electric pushing rod (23), connecting rod (24), and rotating disc (25). Components 20, 21, 22, 23, 24, and 25 work together to establish the regulating mechanism (14). Of those, fixed disc (21) and adjusting disc (22) are cut out of the same fan-shaped opening, and three fan-shaped outlets are evenly distributed along the circumference of the rotating disc (25). The rotating disc (25) is mounted coaxially on the transmission shaft (16), and the transmission shaft is also connected with the output shaft of fertilizing motor (19). The rotating speed of this disc can be adjusted by rotary movements of fertilizing motor (19). The electric pushing rod (23) is associated with the adjusting disc (22) through the connecting rod (24), and a rotating behavior of the disc is achieved by a linear movement of the pushing rod and a linear motor inside it. Combining arrangements of openings on three discs and the adjusting ability of rotary speeds for the adjusting disc (22) and rotating disc (25), a staggered opening for discharging fertilizer must be achieved continuously. Therefore, fertilizer particles fall into the receiving tray (15) under the action of gravity. Moving through the shunt pipe (17), spiral hose (18), and ditcher (20), these particles will be distributed in a banded manner in the groove opened by the ditcher (20). Evidently, rotary speeds of the two motors driving the adjusting disc (22) and rotating disc (25) are crucial to control fertilization performance.

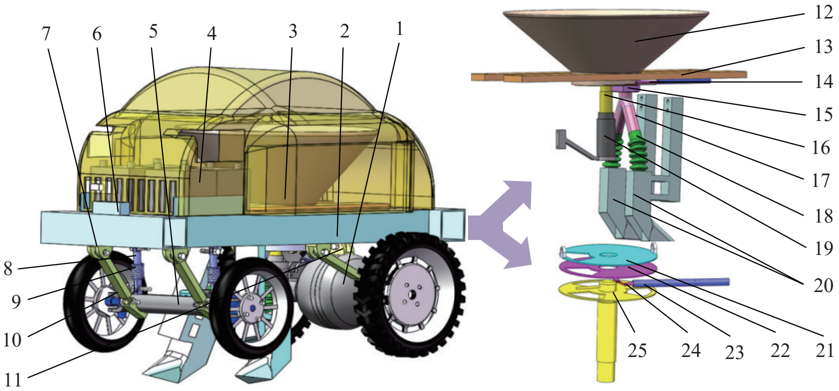


Figure 1 Structural diagram of fertilizing device and vehicle[13]

Vehicle speeds and steering angles are also useful to control the fertilization amount and shapes of fertilization bands, which are adjusted by the respective motors in electric drive subsystems (1) and electric steering subsystems (5). Therefore, the fusion control of four motors is suggested to obtain excellent fertilization performance and a good versatility for plant spacing.

Further considering the requirements for controlling four motors, applications in special areas, and the low cost, the control system is proposed as seen in Figure 2[13]. In detail, such a system includes the mobile phone-based interface, electric control subsystem, and electromechanical subsystem (electric vehicle and fertilization devices). During a work stage, the control command of generating PWM (Pulse Width Modulation) for the fertilizing motor (19) is preprogrammed in the central control unit. The combination of this signal and fertilization unit 1, fertilizing motor (19), and rotating disc (25) will be rotated by a given speed. The duty ratio of PWM for a linear motor inside the electric pushing rod (23) will be semi-actively adjusted by pressing "PUSH ROD" buttons, thus increasing and reducing rotary speeds of the adjusting disc (22) through such a varied PWM signal and fertilization unit 2. In addition, vehicle speeds and steering angles are also controlled by corresponding buttons and driving units. Therefore, the fusing control for this fertilization vehicle can be achieved by such a structural scheme and the semi-active control system.

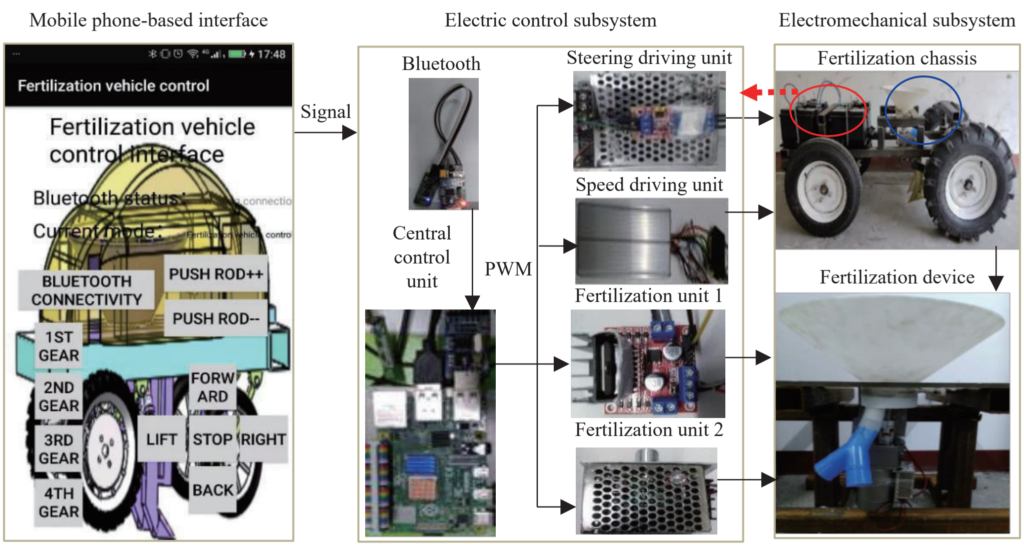


Figure 2 Composition and working principle of control system[13]

3 Integrated simulation in EDEM

Mentioned in Figure 1[13], opening θ, rotational speed n, and moving speed v of the vehicle are controllable factors for varying fertilization amounts and adapting to different plant spacing. The maximum angle of opening of this instance is limited to 50°. Generally, the fertilization amount ranges from 1500 to 6000 kg/hm^2[4,14], and the moving speed of a vehicle varies from 0.2778 to 1.3889 m/s[4,15]. As a result, the fan-shaped opening changes from 35° to 50°. Relative to this range of openings, strokes of the electric-pushing rod vary from 34 to 52 mm[13], and a linear relationship between them is accessible. Therefore, adjustment of the duty ratio of a motor inside the electric-pushing rod is used to control strokes and openings. The planting spacing is usually changed from 0.25 to 4.5 m[1,8,16-19]. Further combining diverse plant distances, vehicle speeds, and fertilization amounts, rotational speeds of the rotating disc vary from 5 to 20 r/min.

Therefore, a simulation model fusing given openings (35-50°), rotating speeds (5-20 r/min), and moving speeds (0.2778-1.3889 m/s) is adopted to evaluate whether the fertilization vehicle can be applied in different plant spacing without any structural adjustment.

In order to carry out such an integrated simulation, the discrete element method (DEM) in the EDEM is utilized in this field[1,20]. The dynamic simulation program combining the entire vehicle, the fertilization device, and fertilizer particles is shown in Figure 3. Firstly, the physical model of fertilizer particles such as the size, shape, and mass ratio was established in the CREATOR module through Stanley fertilizer, and the single model of particle based on given parameters[1,6] is shown in Figure 3a. Secondly, combining the Hertz-Mindlin (no slip) contact model, contact parameters between particles and corresponding solid parts, including other particles, vehicle components, and the soil layer, were defined according to the relevant literature[1,6]. Then, a soil layer 9000 mm in length and 1500 mm in width was arranged directly below the fertilization vehicle geometry shown in Figure 3b. On the basis of this, kinematic characteristics of the soil layer, such as the linear translation and the linear rotation, can be obtained by three-dimensional (3D) coordinate points, portrayed in Figure 3c. Finally, the factory of fertilizer particles was built directly above the circular hopper-type sowing box, and the size of the factory was the same as that of the circular hopper. All models of fertilizer particles were then achieved in this factory, as depicted in Figure 3d. According to simulation and experiment requirements, the total mass of the fertilizer factory was defined as 10 kg, and the production rate was about 3 kg/s. The gravitational acceleration of the fertilizer particles was defined as the Y-direction.

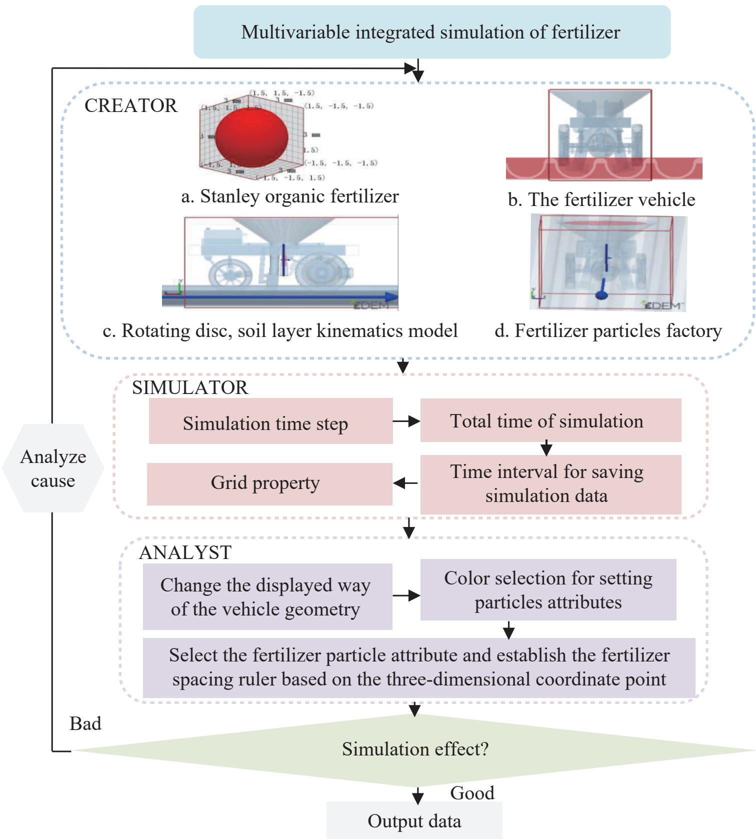
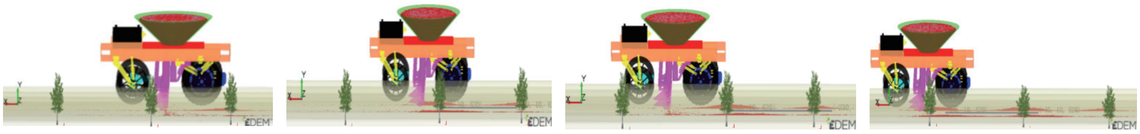


Figure 3 Multivariable integrated simulation program of the fertilizing vehicle based on EDEM

On the basis of the geometric motion, particles, and contact parameters of the fertilizer vehicle, some definitions were completed in the SIMULATOR module. For example, the total simulation time was about 10 s, and time step was defined as 10%. The time interval for saving simulation data was 0.01 s. After achieving the above, dynamic simulations for validating adaptation to different plant spacing were carried out. Completing each simulation, the fertilization spacing corresponding to the plant distance can be clearly depicted in the ANALYST module, which is shown as an instance in Figure 4.

After achieving the simulation as shown in Figure 4, the simulations with a single factor, including the fan-shaped opening, the rotation speed of the rotating disc, and the moving speed of the fertilization vehicle, were carried out, and the other two factors were controlled quantitatively in one-factor experiments. After completing these works, the main factors influencing the spacing of fertilization became clear. On the basis of this result, the certain factor that is independent of the

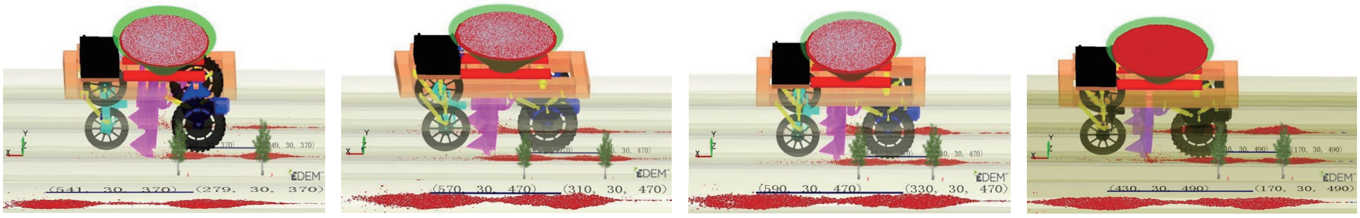


1.59 s 2.59 s 3.59 s 4.59 s

Figure 4 Effect of adaptive root fertilization

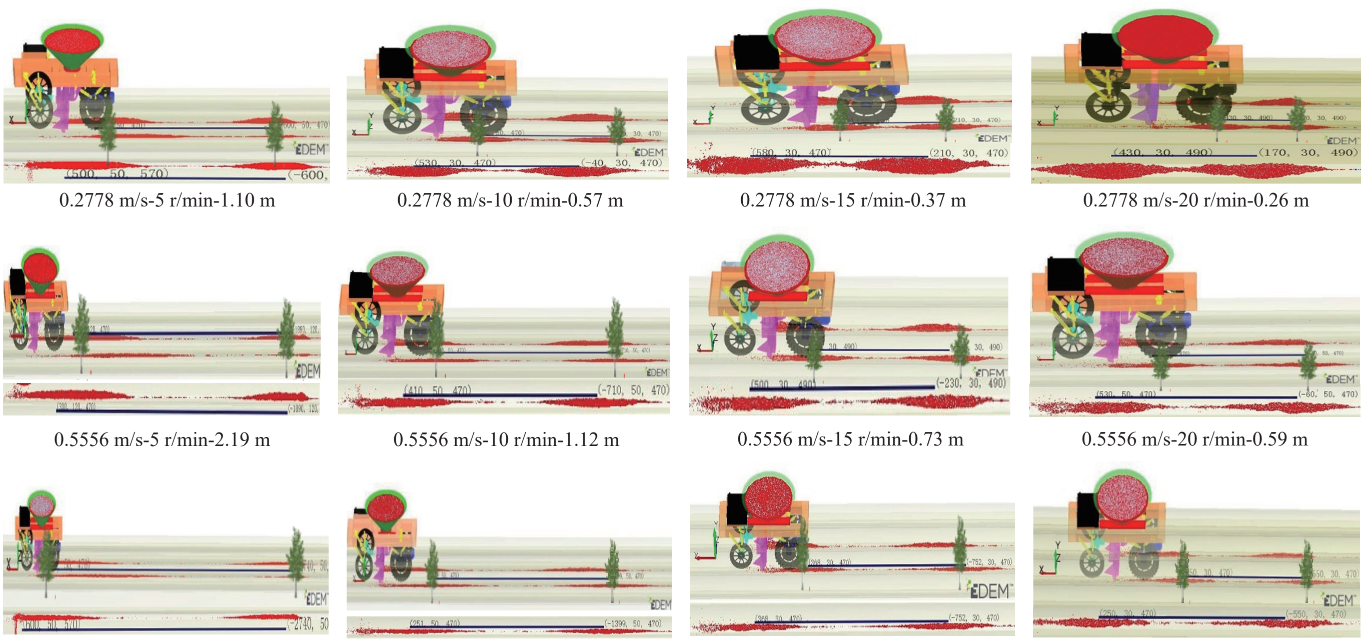
fertilization distance was controlled quantitatively by a control variable method, and the orthogonal experiment related to two factors was carried out, which is beneficial to determine the regulating range of fertilization spacing for different plants and root systems.

For example, at a given moving speed (0.2778 m/s) of the vehicle and rotation speed (20 r/min), fertilization distances were about 0.262 m, 0.26 m, 0.26 m, and 0.26 m if the fan-shaped openings were defined as 35°, 40°, 45°, and 50°. Therefore, the fan-shaped opening is independent of the fertilization spacing, portrayed in Figure 5. The fertilization distances decreased to 0.26 m from 1.1 m if the rotation speed ranged from 5 to 20 r/min at a given moving speed (0.2778 m/s) and fan-shaped opening (50°), as shown in Figure 6. At a given rotation speed (20 r/min) and fan-shaped opening (50°), the fertilization distance varied from 0.26 to 1.41 m. Therefore, the moving speed of the vehicle and rotation speed of the disc are the main factors which determine the fertilization distance. On the basis of this, the fan-shaped opening was controlled quantitatively, such as at 50°, according to the requirements of the amount of fertilization for fruit trees[14]. Simulated results from EDEM under different rotation speeds (5-20 r/min) and moving speeds (0.2778-1.3889 m/s) are depicted in Figures 6 and 7, which characterize a wide range of fertilization distances, from 0.26 to 5.53 m. Therefore, the proper control of the rotation speed of the rotating disc and moving speed of the vehicle is helpful to fertilize in different plant spacing with a type of root fertilization. The comparisons between these results and the experimental data will be demonstrated in Section 4.



0.2778 m/s-35°-0.262 m 0.2778 m/s-40°-0.26 m 0.2778 m/s-45°-0.26 m 0.2778 m/s-50°-0.26 m

Figure 5 Fertilization spacing under the working conditions of rotating disc speed of 20 r/min, vehicle speed of 0.2778 m/s, and fan-shaped opening of 35°-50°



0.2778 m/s-5 r/min-1.10 m 0.2778 m/s-10 r/min-0.57 m 0.2778 m/s-15 r/min-0.37 m 0.2778 m/s-20 r/min-0.26 m

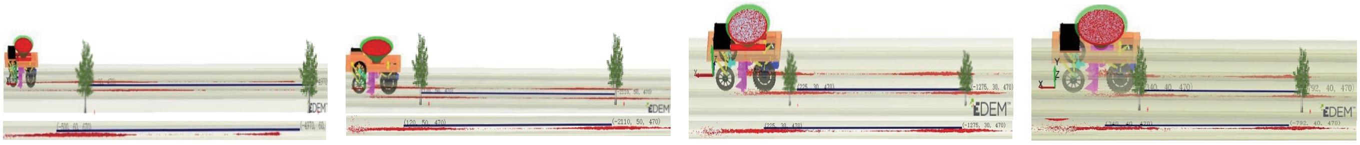
0.5556 m/s-5 r/min-2.19 m 0.5556 m/s-10 r/min-1.12 m 0.5556 m/s-15 r/min-0.73 m 0.5556 m/s-20 r/min-0.59 m

0.8333 m/s-5 r/min-3.34 m 0.8333 m/s-10 r/min-1.65 m 0.8333 m/s-15 r/min-1.12 m 0.8333 m/s-20 r/min-0.80 m

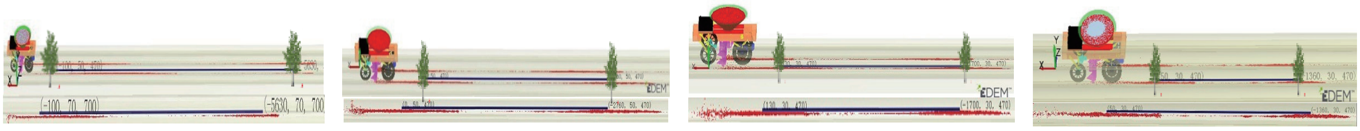
Figure 6 Fertilization spacing under the working conditions of vehicle speed of 0.2778-0.8333 m/s, rotating speed of rotating disc of 5-20 r/min

4 Simulated-field experiments and comparisons with EDEM results

Evidently, the above integrated simulations reveal that the fusing control of multi-variables, such as the fan-shaped opening, rotating speed, and moving speed, is beneficial for fertilization in different plants with a type of root fertilization. However, these simulated results and models should be further validated before



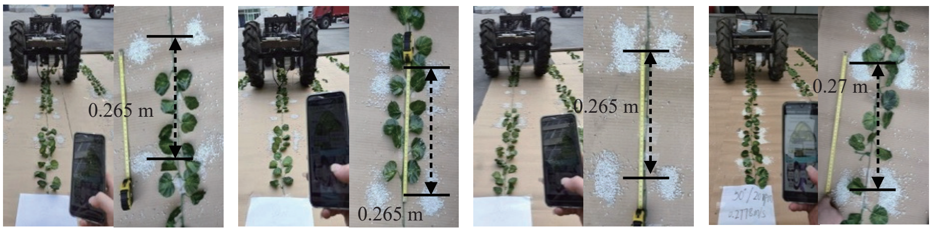
1.1111 m/s-5 r/min-4.47 m 1.1111 m/s-10 r/min-2.23 m 1.1111 m/s-15 r/min-1.50 m 1.1111 m/s-20 r/min-1.13 m



1.3889 m/s-5 r/min-5.53 m 1.3889 m/s-10 r/min-2.76 m 1.3889 m/s-15 r/min-1.83 m 1.3889 m/s-20 r/min-1.41 m

Figure 7 Fertilization spacing under the working conditions of vehicle speed of 1.1111-1.3889 m/s, rotating speed of rotating disc of 5-20 r/min

using these models to guide design. The precision of fertilization distance and the reliability of control system based on a mobile phone program must be determined. Therefore, simulated-field experiments with the same conditions were also carried out. In order to complete these experiments, an electric chassis with the fertilization device was manufactured in a lab. Green grass and paper cloth were utilized to establish a test site with a length of 6 m, a width of 5 m, and a row spacing of 0.6 m. In the experiment, Stanley fertilizer particles were utilized, and their properties were the same as the simulated material. According to the independence of the fan-shaped opening, it was also defined as 50°. The rotating speed varied from 5 to 20 r/min, and the moving speed of the vehicle changed from 0.2778 to 1.3889 m/s. The fertilization motor and the rotation speed of the rotating disc were controlled by corresponding programs in the central control unit. The stroke of electric-pushing rod and the fan-shaped opening were changed by pressing the PUSH ROD++ and PUSH ROD−− buttons through the mobile phone interface. Also by adjusting the speed buttons, the moving speed of the vehicle was varied through this interface, such as 1st, 2nd, 3rd, and 4th. Finally, the test procedures are shown in Figures 8-10.



35°-0.265 m 40°-0.265 m 45°-0.265 m 50°-0.27 m

Figure 8 Test fertilization spacing under the working conditions of vehicle speed of 0.2778 m/s, rotating speed of rotating disc of 20 r/min, and fan-shaped opening of 35°-50°

As evidently depicted in Table 1, at given moving speeds (0.2778 m/s) and rotating speeds (20 r/min), the fertilization distance under different openings (35°-50°) was about 0.26 m, which is almost consistent with that of the EDEM result. The absolute errors relative to simulated results ranged from 0.003 to 0.01 m. Also drawn from these data, the fan-shaped openings are not a main factor in controlling the fertilization distance. Therefore, at a given opening such as 50°, the fertilization distance under different moving speeds (0.2778-1.3889 m/s) and rotating speeds (5-20 r/min) was tested. Each test was carried out three times, and the average result was taken as the final one.

Table 1 Comparison of fertilization spacing under different openings

Fan-shaped opening/(°)	Fertilization spacing/m		
	EDEM	Test	Absolute error
35°	0.262	0.265	0.003
40°	0.26	0.265	0.005
45°	0.26	0.265	0.005
50°	0.26	0.27	0.01

As obviously depicted in Table 2, the fertilization distance varied from 0.27 to 5.45 m. Standard deviations ranged from 0.01 to 0.102 m, and the maximum and minimum coefficients of variation were 6.15% and 1.61%, respectively. Further comparing with simulated results as shown in Table 3, the absolute error changed

Table 2 Test result of fertilization spacing under different moving speeds and rotating speeds

Moving speed/ m·s⁻¹	Rotating speed/ r·min⁻¹	Fertilization spacing/m					
		1	2	3	Average	Standard deviation	Coefficient of variation/%
0.2778	5	1.12	1.16	1.17	1.15	0.027	2.30%
	10	0.61	0.58	0.61	0.60	0.017	2.89%
	15	0.40	0.40	0.37	0.39	0.017	4.44%
	20	0.27	0.28	0.26	0.27	0.010	3.70%
0.5556	5	2.13	2.13	2.19	2.15	0.035	1.61%
	10	1.08	1.04	1.09	1.07	0.027	2.47%
	15	0.69	0.73	0.71	0.71	0.020	2.82%
	20	0.59	0.55	0.57	0.57	0.020	3.51%
0.8333	5	3.34	3.3	3.23	3.29	0.056	1.69%
	10	1.61	1.58	1.67	1.62	0.046	2.83%
	15	1.1	1.06	1.11	1.09	0.027	2.43%
	20	0.83	0.77	0.83	0.81	0.035	4.28%
1.1111	5	4.46	4.40	4.31	4.39	0.076	1.72%
	10	2.12	2.17	2.22	2.17	0.050	2.30%
	15	1.42	1.51	1.48	1.47	0.046	3.12%
	20	1.10	1.04	1.13	1.09	0.046	4.20%
1.3889	5	5.47	5.34	5.54	5.45	0.102	1.86%
	10	2.72	2.60	2.78	2.70	0.092	3.39%
	15	1.87	1.70	1.8	1.79	0.085	4.77%
	20	1.35	1.24	1.40	1.33	0.082	6.15%

Figure 9 Fertilization spacing under the working conditions of vehicle speed of 0.2778-1.1111 m/s, rotating speed of rotating disc of 5-20 r/min

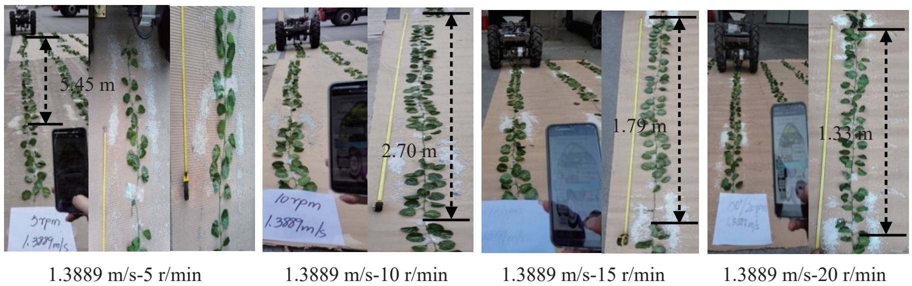


Figure 10 Fertilization spacing under the working conditions of vehicle speed of 1.3889 m/s, rotating speed of rotating disc of 5-20 r/min

from −0.08 m to 0.05 m, and the relative error varied from −5.67% to 5.41%. Therefore, the variable fertilization distance with high accuracy under different moving speeds and rotating speeds has been achieved in practice. The control system and structural schemes are feasible. Simulated results and models are also reliable.

Completing evaluation of precision of fertilization distance based on the mentioned mobile phone programs, the uniformity and stability of fertilization amount applied to the root system was also estimated. The experiment for a single factor was carried out. Each test was repeated three times, and the average amount was taken as the final result. For example, at given fan-shaped openings (35°-50°) and rotating speeds (5-20 r/min), the fertilization amount of a fan-shaped leakage opening without moving speeds is portrayed in Figure 11a. As evidently shown in Figure 11a, the fertilization ranged from 34.92 to 246.62 g. As demonstrated in Figure 11b, the standard deviation of the three tests varied from 1.1787 to 2.9963 g

Table 3 Comparison of fertilization spacing under different moving speeds and rotating speeds

Moving speed/m·s⁻¹	Rotating speed/r·min⁻¹	Fertilization spacing/m			
		EDEM	Test	Absolute error	Relative error/%
0.2778	5	1.10	1.15	0.05	4.55%
	10	0.57	0.60	0.03	5.26%
	15	0.37	0.39	0.02	5.41%
	20	0.26	0.27	0.01	3.85%
0.5556	5	2.19	2.15	−0.04	−1.83%
	10	1.12	1.07	−0.05	−4.46%
	15	0.73	0.71	−0.02	−2.74%
	20	0.59	0.57	−0.02	−3.39%
0.8333	5	3.34	3.29	−0.05	−1.49%
	10	1.65	1.62	−0.03	−1.82%
	15	1.12	1.09	−0.03	−2.68%
	20	0.80	0.81	0.01	1.25%
1.1111	5	4.47	4.39	−0.08	−1.79%
	10	2.23	2.17	−0.06	−2.69%
	15	1.50	1.47	−0.03	−2.00%
	20	1.13	1.09	−0.04	−3.54%
1.3889	5	5.53	5.45	−0.08	−1.45%
	10	2.76	2.70	−0.06	−2.17%
	15	1.83	1.79	−0.04	−2.19%
	20	1.41	1.33	−0.08	−5.67%

under the same conditions, and the maximum and minimum coefficients of variation were 4.04% and 1.02%, respectively.

The variation coefficient reached maximum at the rotating speed of 20 r/min. Further combining different moving speeds (0.2778-1.3889 m/s) and fan-shaped openings (35°-50°), the standard deviation changed from 1.4136 to 4.7985 g. The maximum and minimum coefficients of variation were 9.28% and 4.73%, respectively, when the rotating speed was about 20 r/min, as shown in Figure 11c. The variation coefficient increased with larger moving speeds, and it reached maximum at a speed of 1.3889 m/s. Under these conditions, the fertilization amount varied from 34.75 to 63.23 g, as shown in Figure 11d. Therefore, uniform and stable fertilization can also be achieved.

5 Conclusions

It is difficult to meet the requirements of different plant spacing by completely relying on mechanical schemes, and the simulation method based on a single variable is also unfavorable to determine the effect of fusion factors on fertilization distances and amounts. Improvements in this field will be achieved by the following measures:

(1) An electric-fertilizing vehicle with a fan-shaped leakage device and mobile phone-based programs can adjust the fertilization distance and amount with high accuracy, and the fusing control of different factors such as rotating speeds (5-20 r/min), openings (35°-50°), and moving speeds (0.2778-1.3889 m/s) is beneficial for meeting the requirements of different plant spacing.

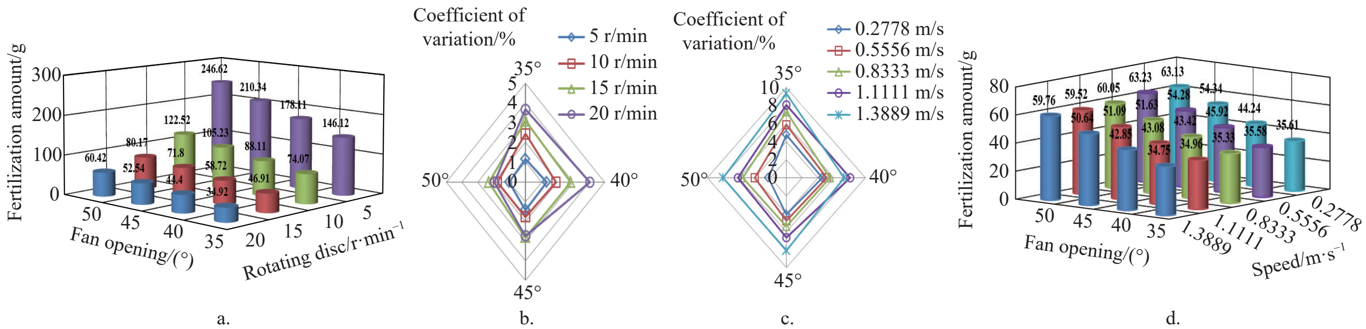


Figure 11 Effects of fan opening and rotating speed of rotating disc on fertilization amount (a), coefficient of variation (b); Effect of fan opening and moving speed on coefficient of variation (c) and fertilization amount (d)

(2) On the basis of the discrete element method (DEM) and the numerical simulation software EDEM, an integrated simulation model including the fertilization vehicle, leakage device, fertilizer factory, and soil layer can be used to directly determine unrelated factors for the fertilization spacing and present the fusing effects of the main factors on fertilization distances. The opening is independent of such a fertilization spacing, and it will be mainly determined by rotating speeds (5-20 r/min) and moving speeds (0.2778-1.3889 m/s). Under these conditions, simulated results of fertilization distance range from 0.26-5.53 m, which can be utilized in fields of root fertilization with different plant spacing, thus demonstrating good versatility and the feasibility of the structural scheme.

(3) In the experiment with the fusing control of multivariable, the fertilization spacing changes from 0.27 to 5.45 m under different moving speeds (0.2778-1.3889 m/s) and rotating speeds (5-20 r/min). The standard deviation of repeated experiments ranges from 0.01 to 0.102 m, and the maximum and minimum coefficients of variation are 6.15% and 1.61%, respectively. Compared with the simulated data, the absolute error varies from −0.08 to 0.05 m, and relative error ranges from −5.67% to 5.41%. Therefore, the designed electric vehicle with a fan-shaped leakage device and the mobile phone-based program is favorable for fertilization of different plants, and the proposed simulation model is feasible, thus presenting a good reference for designing these components.

(4) Without movements of the vehicle, the average fertilization amount of a fan-shaped leakage opening increases from 34.92 g to 246.62 g at given openings (35°-50°) and rotating speeds (5-20 r/min). The standard deviation of the three tests varies from 1.1787 to 2.9963 g, and the maximum and minimum coefficients of variation are 4.04% and 1.02%, respectively. The variation coefficient is largest if the rotating speed is up to 20 r/min. Under such a rotation speed, the average amount of the fan-shaped leakage opening ranges from 34.75 to 63.23 g as long as the openings (35°-50°) and moving speeds (0.2778-1.3889 m/s) are controlled properly. The standard deviation changes from 1.4136 to 4.7985 g. The maximum and minimum coefficients of variation are 9.28% and 4.73%, respectively.

It can be concluded from the above investigation that the proposed schemes and control programs can be used to fertilize in different plant distances, and the fertilization amount is also uniform and stable. The proposed simulation model has presented high accuracy and a good reference for designing these devices.

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[References]

[1] Du X, Liu C, Jiang M. Design and development of fertilizer point-applied device in root-zone. Applied Engineering in Agriculture, 2022; 38(3): 559–571.

[2] Timilsena Y P, Adhikari R, Casey P. Enhanced efficiency fertilisers: a review of formulation and nutrient release patterns. Journal of the Science of Food, 2015; 95(6): 1131–1142.

[3] Jiang C, Lu D, Zu C. One-time root-zone N fertilization increases maize yield, NUE and reduces soil N losses in lime concretion black soil. Scientific Reports, 2018; 8(1): 1–10.

[4] Fu Z, Dong Y, Zhang L. Design and simulation of automatic fertilizing machine for greenhouse. Transactions of the CSAE, 2017; 33(1): 335–342.

[5] Chen H B, Zheng J F, Lu S J, Zeng S, Wei S L. Design and experiment of vertical pneumatic fertilization system with spiral Geneva mechanism. Int J Agric & Biol Eng, 2021; 14(4): 135–144.

[6] Guo H, Fang L Y, Ye Y Q, Yang W W, Wang Z Q, Liu Z T, et al. Design and test of the disk-type variable-rate fertilizer feeder based on EDEM. Journal of Machine Design. 2019; 36(9): 67–71.

[7] Zhang R, Wang X, Zhao C J, Bai Y L, Meng Z J, Chen L P. Design and experiment of variable rate fertilizer spreader with conveyor chain. Transactions of the CSAE, 2012; 28(6): 20–25.

[8] Liu J, Zhu D Q, Tai Q L, Yu C Y, Wang T J, Xue K, et al. Design and experiment of adjustable socket-wheel precision fertilizer apparatus for dry direct-seeding rice. INMATEH-Agricultural Engineering, 2021; 63(1): 121.

[9] Chen C, Pan J J, Lam S K. A review of precision fertilization research. Environmental Earth Sciences, 2014; 71(9): 4073–4080.

[10] Van Liedekerke P, Tijskens E, Dintwa E, Anthonis J, Ramon H. A discrete element model for simulation of a spinning disc fertilizer spreader I: Single particle simulations. Powder Technology, 2006; 170(2): 71–85.

[11] Yang L, Chen L, Zhang J. Fertilizer sowing simulation of a variable-rate fertilizer applicator based on EDEM. IFAC-PapersOnLine, 2018; 51(17): 418–423.

[12] Bangura K, Gong H, Deng R L, Tao M, Liu C, Cai Y H, et al. Simulation analysis of fertilizer discharge process using the Discrete Element Method (DEM). PloS one, 2020; 15(7): e0235872.

[13] Zhang L, Yuan X J, Qiu T Y. Design and experiment for a small electric-fertilization vehicle with a mobile phone-based program. Journal of the Brazilian Society of Mechanical Sciences and Engineering, 2023; 45(12): 633.

[14] Shi L, Xu L M, Xing J, Yuan Q, Liu X, Chen J, et al. Design of fertilization control system based on EDEM simulation for deep application of organic fertilizer. Journal of China Agricultural University, 2018; 23(1): 121–132.

[15] Zhuang S, Komats M U. Automatic feeding control of fertilizer applicator and seeder based on running speed signals (Part 1) Development of Control device and feeding performances of seed and fertilizer. Journal of the Japanese Society of Agricultural Machinery, 1996; 58(1): 49–55. (in Japanese)

[16] Hart W E, Gaultney L D. Citrus tree spacing effects on soil water use, root density, and fruit yield. Transactions of the ASAE, 1991; 34(1): 129–134,

[17] Pan R, Meng Z J, Dong J J, Shang Y H, Mei H B, Yan B X, et al. Design and testing of an intermittent fertilisation method for seeding of maize (*Zea mays*). Crop and Pasture Science, 2022; 73(3): 203–213.

[18] Zhang X H, Toudeshki A, Ehsani R, Li H L, Zhang W F, Ma R J. Yield estimation of citrus fruit using rapid image processing in natural background. Smart Agricultural Technology, 2022; 2: 100027.

[19] Osman M S, Elamin O M, Elkashif M E. Effect of planting method and spacing on growth, yield and fruit characteristics of papaya fruit (*Carica papaya* L.). Gezira Journal of Agricultural Science, 2012; 10(2): 15–30. http://journals.uofg.edu.sd/index.php/gjas/article/view/2484

[20] Hwang S-J, Nam J-S. DEM simulation model to optimise shutter hole position of a centrifugal fertilizer distributor for precise application. Biosystems Engineering, 2021; 204: 326–345.